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ELECTRON BEAM GENERATED HOLOGRAPHIC OPTICAL ELEMENT RESEARCH

Annual Technical Report

January 1, 1981 to December 31, 1981

Submitted to
Air Force Office Of Scientific Research

May 1982

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This report describes progress of the e-beam generated holographic optical element research program during 1981. We investigated partitioned computer generated holographic masks for optical matrix-vector multiplication. These masks are partitioned into separate areas for each channel, with each of these areas containing a linear grating to diffract light to its designated detector. A single lens completes the optical system. The space variant properties of the mask allow post-fabrication trimming for amplitude control. We have —

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demonstrated the optical equivalent of a 1 x 10 matrix operation. In separate experiments, we have encoded matrices with numerical accuracies of 20 dB and a numerical range of 37 dB. These results were limited primarily by the stability of the input light source.

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Table of Contents

List of Illustrations

PREFACE

This report was prepared by Honeywell Corporate Technology Center. The research work was sponsored by the Air Force Office of Scientific Research under Contract No. F49620-80-C-0029.

This annual technical report covers work performed between 1 January 1981 and 31 December 1981. The contract monitor is Dr. John A. Neff, Program Manager of Electronics and Material Sciences, AFOSR/NE, Building 410, Bolling Air Force Base, Washington, D.C., 20332. The principal investigator is Steven M. Arnold. Steven K. Case of the University of Minnesota serves as consultant to this program.

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Section I
Introduction

This report describes the research activities in the second year of a four-year effort to investigate holographic optical elements (HOEs) generated by e-beam lithography. HOEs can play an important role in many areas of optical engineering and research. They offer many advantages over conventional optical systems, most notably: compactness, light weight, and low cost. Many research groups have demonstrated HOEs in practical optical systems. HOEs have been employed as optical components in interferometers (Ref. 1) wherein they provide a reference wavefront for comparing optical surfaces. They also have been used in laser machining to shape the laser (Ref. 2). In 1979, Fienup and Leonard demonstrated that holographic optics are capable of processing images of large space-bandwidth product for use in optical processors (Ref. 3). More recently, Horner and Ludman have also shown the use of HOEs for demultiplexing in fiber-optic systems (Ref. 4). To be more compatible in existing optical systems, these elements must have the following qualities: high diffraction efficiency over the desired field of view, low scattering, low aberrations, and low cost.

The advance of digital holography has opened a new frontier in holographic optics. It is by far the best technique for fabricating optical elements to form wavefronts of arbitirary complexity. Techniques for making binary computer-generated holograms (CGHs) are well developed. Their potential in optical engineering applications is ever increasing. CGHs have been used in such areas as optical data processing, optical testing, optical memories, laser beam scanning, and 3D image display. An article by W.H. Lee (Ref. 5) is an excellent source of information on both the techniques of making CGHs and their applications. With the discovery of improved fabrication techniques, more applications of CGHs are to be anticipated in the future.

The computer generation of a hologram involves the following three major steps:

- Calculation of the complex wavefront at the hologram plane originating from a given wavefront at the object plane. (This is done by ray tracing or by calculating the Fresnel-Fraunhoffer integral.)
- Encoding of the analog wavefront into an equivalent digital representation. (The Lohmann technique and the Lee technique are the best-known encoding techniques.)
- Fabrication of the hologram by translating the digital, mathematical representation to a recording medium using graphic plotting.

The typical procedure for making the synthetic hologram is to have the digitized interference pattern, which has been calculated and encoded by computer, drawn to a large scale by a computer-driven plotter. The drawing is then reduced photographically onto high-resolution film to the final size desired.

There are several disadvantages and inherent limitations with this procedure: 1) errors are introduced in the plotting and in the photo reduction process; 2) optical recording devices to generate CGHs are limited in spatial resolution and space-bandwidth product, typically to 10^6 pixels; and 3) the turnaround time for the indirect procedure from plotting to photo reduction to film development can be days, which is impractical for industrial applications. E-beam lithography can overcome all of the above disadvantages and limitations. Errors can be significantly reduced because of direct writing and excellent spatial resolution. The achievable number of pixels ($>10^{10}$) can approach that of conventional off-axis optical holograms because of the submicron resolution in direct writing and the capability of having many small scan fields (typically a few millimeters each) stitched together by interferometrically controlled translation of the workpiece. An advanced e-beam lithographic system can easily produce a hologram directly onto a 3-inch wafer in 20 minutes, offering a much shorter turnaround time for practical applications when compared to indirect plotting.

In the following sections, we will list the long-range and annual research objectives of the program (Section II) and then report in detail the status of our research effort for 1981 (Section III). Finally, we will describe briefly the current research program (Section IV).

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Section II
Technical Objectives

We have a very active research program in e-beam lithography at Honeywell to develop VLSI technology and electron-resist materials. A four-year research program to employ e-beam lithography to make CGHs and HOEs for use in optical testing and optical data processing, as well as other optical research of current interest. was proposed to AFOSR in March, 1979.

LONG-RANGE OBJECTIVE

Our overall long-range objective is to:

- Investigate and develop unique HOEs using e-beam lithography and to advance the fundamental knowledge of CGH technology for applications in optical research of current and future interest.

The presently funded program under AFOSR Contract No. F49620-80-C-0029 initiated this research activity at Honeywell beginning on 1 January 1980.

1980 OBJECTIVE

Our short-term objective for the 1980 research program was to:

- Evaluate the quality of e-beam writing and demonstrate the feasibility of using e-beam lithography to generate high-performance synthetic holograms for use in aspheric testing.

During the 1980 program, our efforts concentrated on evaluating the quality of e-beam writing using the existing Honeywell e-beam system and the plane wave interference technique, while, at the same time, performing a distortion analysis of a state-of-the-art optical recording device. These studies advanced our understanding in making compact CGHs by e-beam direct writing. The results of computer plotter distortion analysis further confirmed the superiority of e-beam lithography in making CGHs by indirect plotting. An optimized software to efficiently encode aspheric wavefronts of arbitrary complexity was developed. We generated and tested a synthetic hologram of a nonsymmetric aspheric wavefront to demonstrate the feasibility of writing a complex CGH by e-beam lithography. This technology is now being used to test aspheric diamond-turned optics at Honeywell's Electro-Optics Operations.

1981 OBJECTIVES

As a continutation of our effort to develop unique HOEs using e-beam lithography, we proposed in 1981 to investigate and develop a new kind of HOE, namely, the partitioned computer-generated hologram (PCGH) for optical computing.

Our short-term objectives for the 1981 research program were:

- Analyze and develop capabilities for fabricating partitioned computer-generated holograms using the unique capabilities of e-beam direct writing.
- Demonstrate PCGHs applicable to optical computing, with maximum numerical range >40dB and maximum accuracy >40dB.

The work statement that addressed these objectives consisted of the following five tasks:

1. Develop approaches to the design of PCGHs for optical computing, offering large numerical range, high accuracy, optical efficiency, and the capability of trimming for amplitude control.
2. Calculate achievable values of numerical range, accuracy and computational throughput as a function of space-bandwidth product, optical source characteristics, and mechanical positioning stability. Identify suitable partitioning algorithms which produce PCGHs satisfying specific system requirements.
3. Compare calculated capabilities of the PCGH with the space-invariant hologram and other approaches to optical computing to quantify merits of the space-variant approach.
4. Implement partitioning algorithms to produce PCGHs by e-beam lithography. Develop techniques for trimming.
5. Fabricate and test e-beam PCGHs distributing a Gaussian He-Ne laser beam to 10 outputs. Separate experiments will seek to demonstrate:
   a) Numerical range >40dB
   b) Accuracy >40dB
   c) Optimum combination of numerical range and accuracy.

In the following sections, we will report our significant accomplishments and progress towards achieving these research objectives and summarize the future plan of the program.

Section III
Status of Current Program

There has recently been considerable interest in optical computing since it offers very high computation throughput rates for mathematical operations amenable to parallel computation. One class of such operations, vector-matrix multiplication, can be used for performing discrete Fourier transforms, coordinate transformations, pattern classification, and many other computations. The general matrix-vector multiplication may be written as:

$$y_m = \sum_{n=1}^{N} H_{mn} x_n \quad (m = 1,2, \ldots M).$$

One optical approach to performing this computation uses N light sources to represent the components x_n of the input vector, M detectors to represent the components y_m of the output vector, and suitable optics to assure that a fraction H_{mn} of the light from source x_n gets to each detector y_m. The problem can be suitably scaled so that all parameters fall within acceptable positive ranges. Optics to perform the function of the matrix H will generally be fixed, while the sources are modulated to represent various input vectors x.

In principle, the performance of this optical computer is dependent on a number of considerations involving the optics, detectors, and sources. In practice, numerical range and accuracy are often limited by matrix element imperfections, while speed is limited by the amount of light reaching the detectors. For this reason, our work has focused on efficient optics to precisely distribute light among the various detectors.

In most schemes for optical vector-matrix multiplication, the matrix is encoded as a rectangular array of apertures or gray tones in a mask. This approach, represented in Figure 1, encounters several limitations. A complex optical system is required in order to illuminate and receive light from specific columns and rows of the matrix mask. Much light is discarded in providing uniform illumination to the mask, with the mask passing

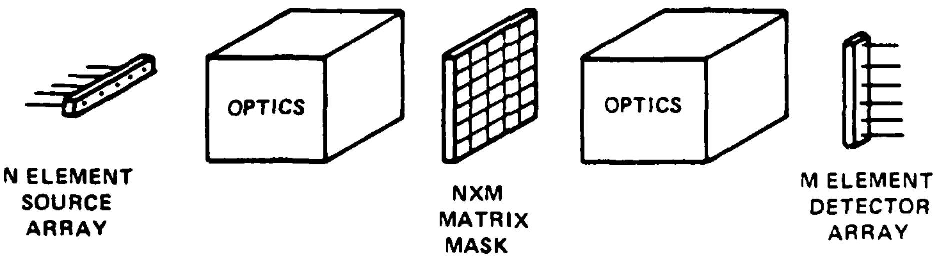

Figure 1. A General Scheme for Optical Vector-Matrix Multiplication

only about half of what remains. Numerical range and accuracy are limited by the space-bandwidth product of the mask (generally less than 10^6 with conventional plotting techniques). Small matrix elements result in small apertures with low relative accuracies. If results differ from those intended, it is generally difficult to modify a mask except by starting anew.

PCGH CONFIGURATION

Our approach to optical vector-matrix multiplication is based upon an e-beam generated diffractive mask which we call a partitioned computer-generated hologram (PCGH) (see Figure 2). Each of N PCGHs is illuminated by collimated light from a single element of the source array and thus represents one column of the N×M matrix mask depicted in Figure 1. Each PCGH is partitioned into M linear gratings which diffract light to the M detectors. The optical power diffracted by a particular grating is made proportional to the value of the required matrix element.

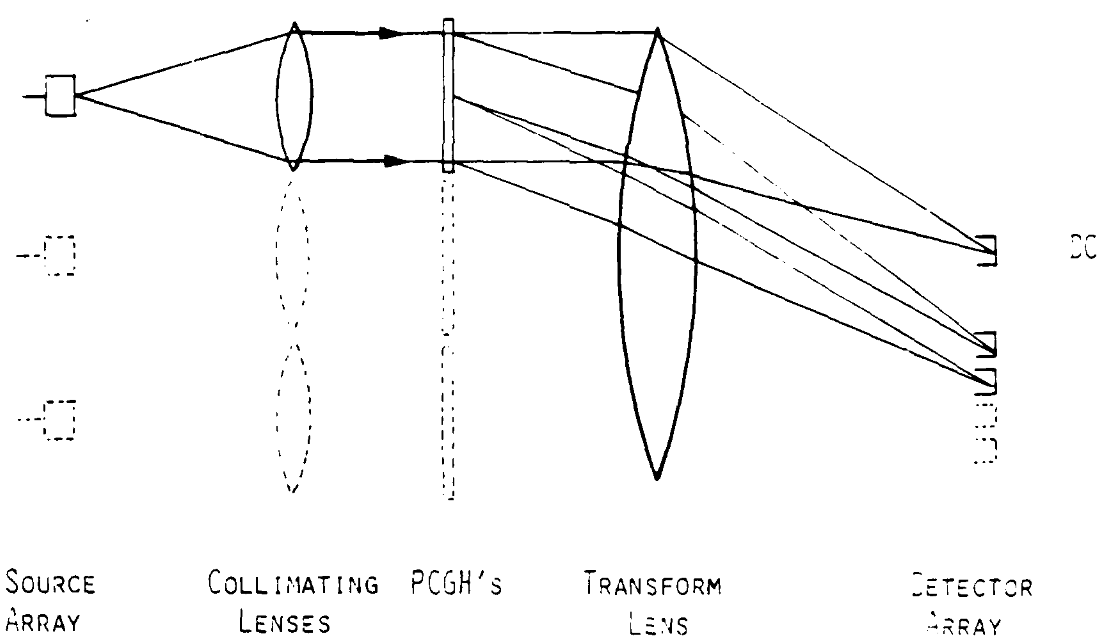

Figure 2. PCGH Vector-Matrix Multiplier. The several facets of each PCGH contain linear gratings which deflect portions of the light to the various detectors. Because of their common Fourier transform lens, the system is insensitive to translation of the source:collimating lens:PCGH modules.

Figure 3 illustrates a PCGH intended to produce 10 equal intensity outputs when uniformly illuminated. This PCGH contains 10 equal area gratings, each with its own spatial frequency. Facets are arranged symmetrically about the center to provide immunity to beam wander.

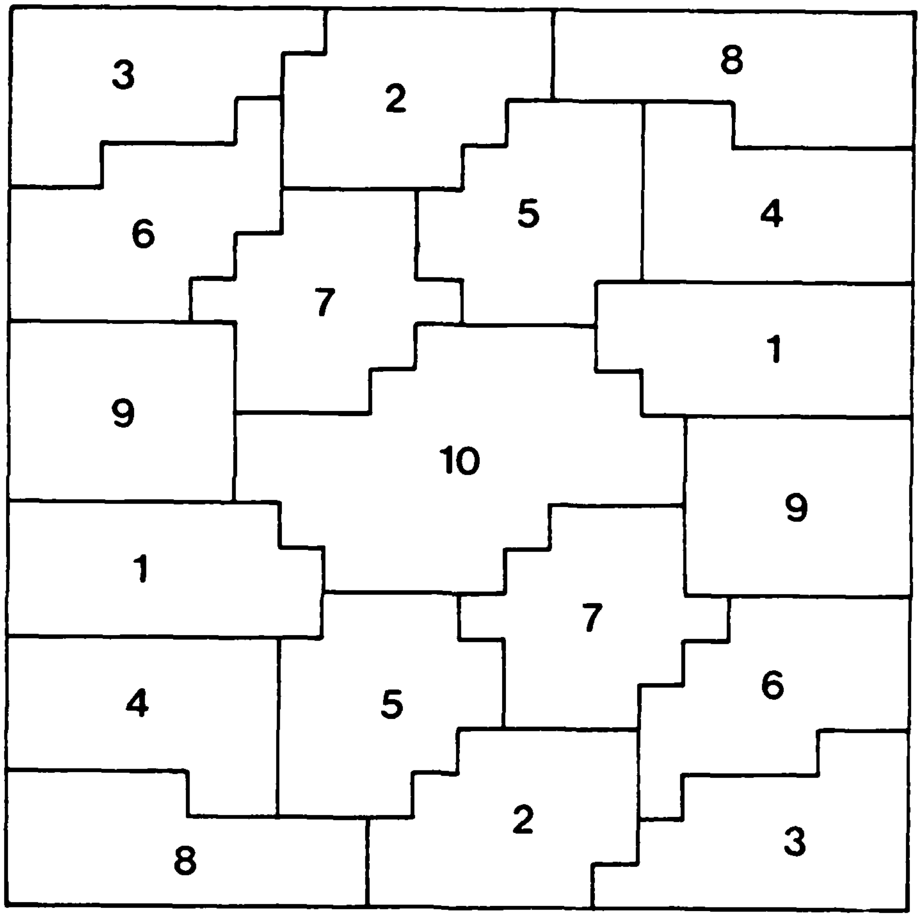

Figure 3. PCGH Design No. 2. This hologram was designed for uniform illumination and 10 equal intensity outputs. Facets are arranged symmetrically about the center to provide immunity to beam wander.

The PCGHs are fabricated as binary chrome-on-glass holograms where the pattern is delineated via e-beam lithography. A glass plate is first coated with a layer of chrome and a layer of e-beam resist. A pattern is exposed in the resist by e-beam direct writing and the resist is developed. The developed resist then serves as a mask for etching the pattern into the chrome.

Our e-beam PCGH optical vector-matrix multiplication scheme has several advantages over the scheme in Figure 1. E-beam lithography offers a higher space-bandwidth product, which can translate into greater numerical accuracy. Also, the PCGHs are in the Fourier plane of the transform lens with respect to the detectors. This means that the only requirement for light to reach a particular detector is that it be traveling in the right direction upon leaving the PCGH. Therefore, the input modules, consisting of source, collimating lens, and PCGH, may be located anywhere within the aperture of the transform lens. This same immunity to translation allows a PCGH to be partitioned into facets in any manner consistent with dividing up the available light amongst the various detectors (providing, of course, that the facets do not become too small). Other advantages relate to optical efficiency. All light striking the PCGH can be used. Light need not be wasted in achieving uniform illumination; non-uniform illumination is acceptable so long as its effects are accounted for in the partitioning. Small facets associated with lesser outputs can be made physically larger by placing them where PCGH illumination is lowest. The various considerations which affect the design of a PCGH are discussed in the following sections.

PCGH DIFFRACTION ANALYSIS

Each facet of the PCGH contains a linear grating to diffract incident light to the appropriate detector. The spatial frequencies of these linear gratings are determined by the system geometry. First-order diffracted light from a facet of spatial frequency ν will be focused in the detector plane distance $\nu\lambda$ F from the transform lens axis (Figure 1), where λ is the wavelength and F the transform lens focal length. Our design is for a 10-element linear detector array. This requires 10 equally spaced grating frequencies $n\Delta\nu$, where $\Delta\nu$ is the frequency separation and n = 10, 11, 12, 13, 14, 15, 16, 17, 18, and 19. The unwanted harmonic frequencies from the square wave gratings begin at $20\Delta\nu$ and will not coincide with the desired outputs.

The matrix values are encoded into the PCGH via grating area modulation. The hologram must therefore be divided into facets such that the amount of light diffracted by a facet to its detector is proportional to the required matrix element. Various considerations lead us to partition the PCGH into facets along a square grid.

Mathematically, the transmittance of a facet can be regarded as the product of its aperture and an infinite linear grating. By the Fourier convolution theorem, the diffraction pattern of this facet is the diffraction pattern of its aperture convolved with the delta function from the infinite linear grating. In other words, the effect of the linear grating is to shift the location of the diffraction pattern of the facet aperture.

Figure 4 indicates the diffraction pattern due to a square aperture of dimension D. The main lobe has a width of $2\lambda F/D$ and contains 81.5 percent of the energy passing through the aperture. The sidelobes form a rectangular array with sidelobe energy diminishing inversely as the square of the distance from either axis. The figure indicates the energies (in dB) of the various sidelobes relative to the main lobe, which has been labeled 0dB. It is seen that their energies diminish most rapidly along the diagonals.

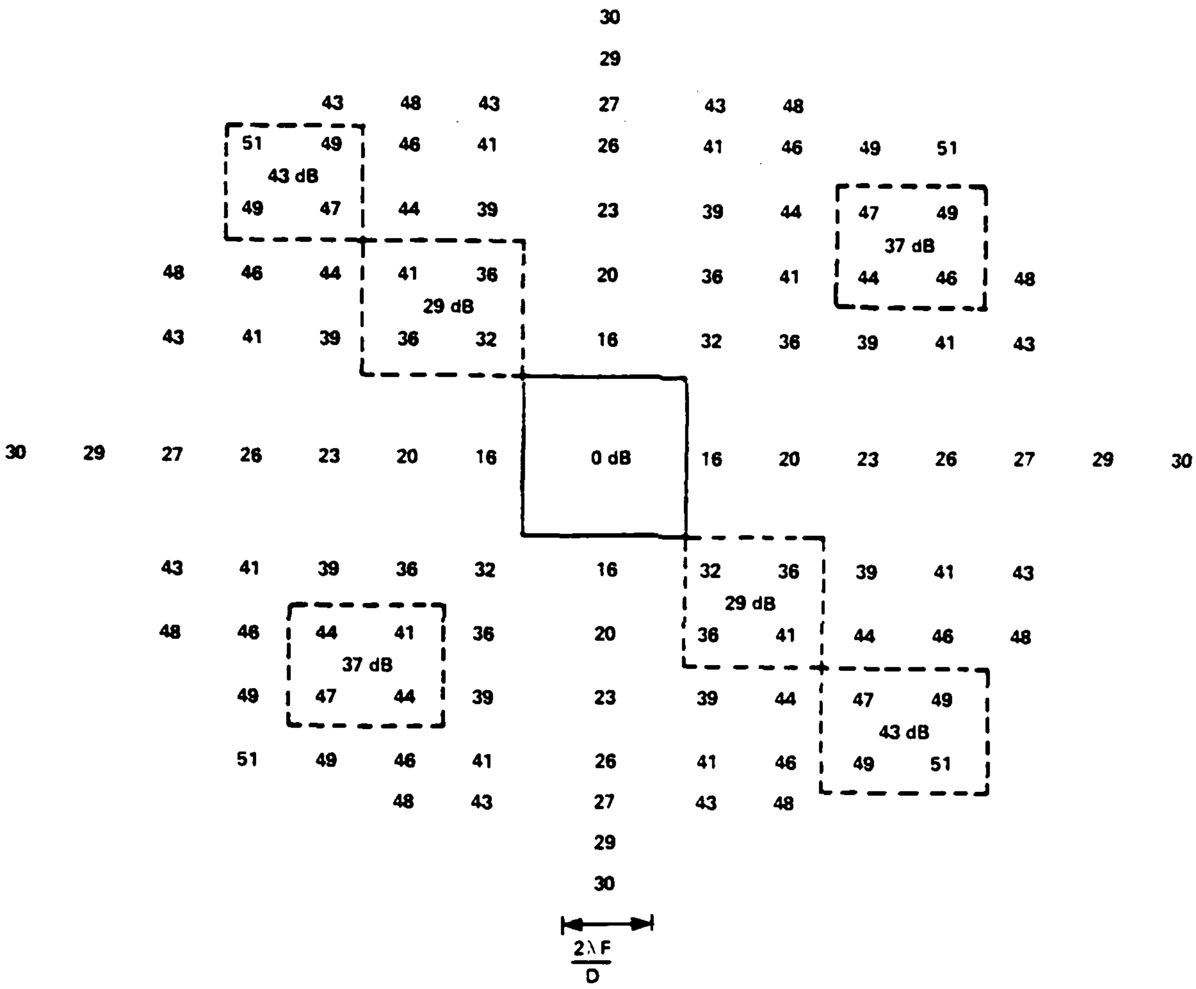

Figure 4. Square Aperture Diffraction and Cross-Talk. The figure illustrates possible detector locations within the diffraction pattern of a single, square aperture. Sidelodes of this diffraction pattern are labeled with numbers indicating their energies (dB) relative to the main lobe. Adjacent identical detectors (dashed boxes) must be separated diagonally to avoid the bright on-axis sidelobes. Locations resulting in 29dB, 37dB and 43dB of channel separation are indicated.

Crosstalk between channels depends on how these diffraction patterns overlap adjacent detectors. As indicated earlier, the separation of detectors is $\Delta\nu\lambda F$. As facets are made smaller, their diffraction patterns become larger, requiring higher grating frequencies to separate them. For this reason, we impose a minimum square facet size, based on the detector separation and an acceptable level of crosstalk. We size our detector aperture to capture only the main lobe of this minimum facet diffraction pattern. A larger aperture would capture lesser lobes of the channel of interest, but also some greater lobes of adjacent channels, thereby degrading the signal-to-noise ratio. Also, having zero intensity at the edges of the detector aperture serves to ease mechanical tolerances.

In the diffraction pattern of Figure 4, the square box in the center, coinciding with the main lobe, represents the detector aperture. Similar boxes are used to indicate possible locations of adjacent detectors. These have been placed diagonaly to use the more rapid sidelobe decay (implying that grating fringes run diagonally within the facets). A separation of $2\lambda F/D$ in each dimension results in 29dB of crosstalk with some very bright axial sidelobes just outside the detector aperture. A separation of $3\lambda F/D$ yields a much more comfortable 37dB crosstalk. With this as our choice, the minimum facet size will be $D = 3\sqrt{2}/\Delta\nu$.

The above discussion of crosstalk implies that each facet is a minimum square facet. This would be a severe constraint on system numerical range. In practice, we form the facet for each channel from many minimum sized modular subfacets. Therefore, the diffraction pattern for a single channel is not that of a single subfacet, but rather the pattern is due to the aperture consisting of all subfacets for that channel. Crosstalk can be minimized by clustering all required subfacets of a given spatial frequency into one or two large facets, such was done in the PCGH of Figure 3. By requiring that large facets be built up of modular subfacets, we have ensured that intensity will fall to zero at the edge of the detector aperture, while the brightest sidelobes will occur away from adjacent detectors, as seen in Figure 5.

To have the greatest flexibility in partitioning the PCGH, we would like the modular subfacets to be as small and numerous as possible. Since they can be no smaller than $D = 3\sqrt{2}/\Delta\nu$ (because of our 37-dB crosstalk limit) we want a large spatial frequency separation $\Delta\nu$. However, a large spatial frequency separation implies large spatial frequencies and hence small grating periods. If the grating period becomes comparable to the e-beam spot size, considerable grating duty cycle variations, with corresponding diffraction efficiency errors, will result. For these reasons we have elected to use grating frequencies of 60 to 114 lp/mm (measured along either axis) and 0.5-mm subfacets. This gives us 400 subfacets in a 1-cm × 1-cm PCGH and a maximum numerical accuracy of about 20dB. With Gaussian illumination, the effective number of subfacets is extended to more than 5000 since the corner facets have about 6 percent of the intensity of illumination of the central facets.

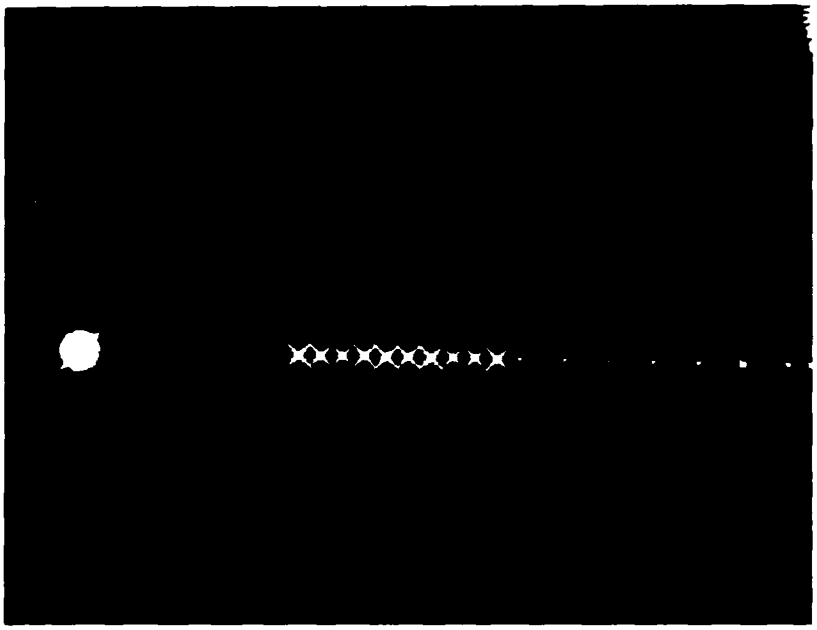

Figure 5. Diffraction Pattern from PCGH Design EQ.8. The undiffracted beam, all 10 first-order diffracted beams, and the first few second-order beams are visible. The latter would be absent if the grating duty cycle were exac ' 50-percent (Ronchi ruling).

PARTITIONING ALGORITHM

The task of partitioning the PCGH to achieve the correct relative outputs has been greatly simplified by our decision to adopt modular facets. The intensities of rectangular facets are easy to compute for either uniform or Gaussian illumination. We need only determine which subfacets are to be assigned to which channels. We do this by means of an algorithm which maximizes accuracy and minimizes crosstalk. Each subfacet is assigned entirely to one channel. With a 1-cm × 1-cm PCGH, 0.5-mm subfacets, and a Gaussian illumination diminishing to e^{-4} at the corners, a subfacet in the corner will receive only 0.00019 of the total energy. Therefore, it is possible to obtain as much as 37dB of numerical range, with no channel receiving less than a full subfacet.

There are a number of possible considerations when deciding which channel gets which subfacets:

- Subfacets for each channel should add up to the correct total intensity.
- Subfacets for each channel should form a single, compact facet.
- In the case of Gaussian illumination facets for the dimmer channels should be located near the edges so that they may be made larger.
- In the case of Gaussian illumination, subfacets for each channel should be located symmetrically about the center so as to provide some immunity to beam wander.

It is generally not possible to simultaneously satisfy each of these criteria. For example, a facet cannot be symmetric about the center, located near the edge, and also compact. Some compromises are necessary.

The partitioning algorithm which we have developed uses a merit function to decide if a particular change to the PCGH is advantageous. The merit function, which embodies the above criteria, is:

$$MF = A \times \sum \left| \text{(intensity-target intensity)/target intensity)} \right|$$

$$+B \times \text{(no. of facet corners)} + (2 \times \text{no. of facet edges)}$$

$$+C \times \sum \left| \text{facet size-average facet size} \right|$$

$$+D \times \text{(no. of asymmetric subfacets)}$$

where the summations are over the various channels. The constants A, B, C and D may be chosen to give any desired emphasis to the four criteria. This merit function is a negative trait in the sense that we wish to minimize it.

The merit function provides a means of distinguishing the better of two partitionings of a PCGH, but it does not tell us which partitionings to consider. With 400 subfacets and 10 channels, there will be 10^{400} possible partitionings! An exhaustive search is out of the question. We have develped two algorithms for partitioning. One algorithm takes a starting PCGH (which may be blank) and considers all changes involving only one subfacet. Changes which would divide existing facets are rejcted. Any other change which reduces the merit function is implemented. Although this algorithm can be rather restrictive, it has tended to work out reasonably well. A second algorithm, which we have also found useful, allows two subfacets to trade their channel assignments. Our partitioning algorithm, like many other optical design programs, is interactive. The operator must guide the program to some extent, redefining the merit function according to how the PCGH is developing and choosing which of the algorithms to apply.

Figure 6 shows the partitioning algorithm at work on a PCGH having 20 × 20 (or 400) subfacets. The goal was a hologram that would produce 10 equal intensity outputs when uniformly illuminated (40 subfacets/channel). The facet boundaries are indicated following the first, last, and one intermediate iteration. This sequence should be compared to Design No. 2 (Figure 3), which included a symmetry criterion in its merit function.

TRIMMING METHODS

To extend our numerical accuracy beyond about 20dB, it is necessary to employ a separate lithography step to adjust the relative amplitudes of the outputs. The ability to do this trimming is one of the chief advantages of e-beam lithography and the PCGH. There are several possible methods of trimming a PCGH once it has been made and tested.

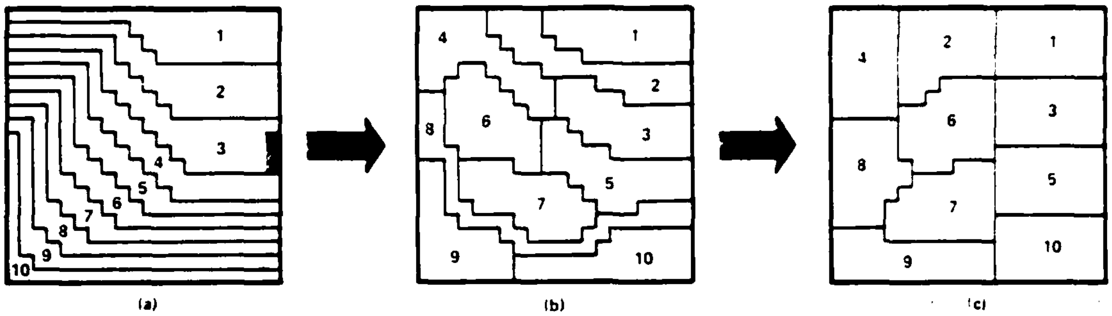

Figure 6. Development of PCGH Design No. 3. This PCGH was designed for uniform illumination and 10 equal intensity outputs. a) After the first iteration, the facets branch from their starting points along the upper left margin. The merit function favored correct intensity and compact facets. b) Several iterations later, most facets have contracted considerably. c) Additional iterations with increased emphasis on compact facets led to this partitioning. The algorithms could find no further improvements.

The best trimming method is to add a negative facet, that is to say, a facet exactly out of phase with the existing facet. This is much easier than it might sound; the negative facet can be written in space already occupied by the existing positive facet, leaving a completely open area. The linewidth and phase problems are overcome since, if we write over the whole area to be trimmed, the phase and duty cycle will be exactly the complement of what was already there.

EXPERIMENTAL RESULTS

The original experimental setup for demonstration and evaluation of PCGHs is indicated in Figure 7. Light from a He-Ne laser is spatially filtered to create a Gaussian point source which is then imaged in the detector plane by a lens. The PCGH is placed after the lens in the optical train and is kinematically mounted on a micropositioner which affords three degrees of translation and one of rotation. Kinematic mounting allows removal for trimming and subsequent replacement of the PCGH without disturbing the alignment. In the detector plane, we have a single UDT-455 photodetector mounted on a motorized translation state. One of several square apertures, selectable in size from 1mm to 2mm, is placed in front of the detector to define and limit its effective area. A mirror diverts the dc beam to a second, identical photodiode whose signal is used to compensate for laser power fluctuations. The two detector signals can be fed into a logarithmic amplifier for rough measurements, or else the signals can be measured directly when greatest accuracy is required.

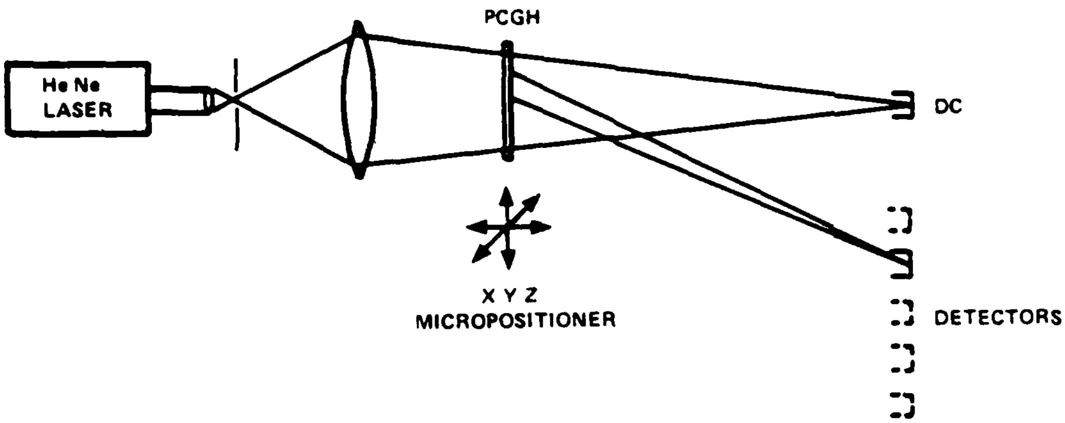

Figure 7. Experimental Setup for Demonstration and Evaluation of PCGHs. A single detector scans across the several output locations while a second detector monitors the undiffracted beam. The PCGH is kinematically mounted to a micropositioner.

Alignment of the setup is straightforward. With the dc mirror removed, the movable detector is positioned to receive maximum signal from the dc beam. The stage is then translated and the PCGH rotated to maximize one of the other outputs. This aligns the outputs with the path of the detector and this alignment is unaffected by subsequent translation of the PCGH. Centering of the PCGH on the optic axis is achieved by equalizing the signals from the two halves of separated symmetric subfacets (e.g., channels 2, 3, 4, 5, and 9 in Figure 8). Each half is obstructed in turn while the detector monitors the relevant channel. If it had occurred to us at the time, we would have provided special facets for this purpose, located just outside the hologram boundaries. Translation of the hologram along the optic axis effectively determines beam diameter, since the beam is converging in this region. Beam diameter is adjusted so as to give best agreement with the design outputs.

The setup as described above was used to evaluate PCGH No. 2 (Figure 3). This hologram was designed to produce 10 equal-intensity outputs when uniformly illuminated. Experimentally, the outputs differed by as much as a factor of two in intensity. Much of this variation could be attributed to non-ideal illumination (a truncated Gaussian).

Rather than tie up the apparatus waiting for PCGH No. 2 to be trimmed, we proceeded immediately to experiments which would utilize the full Gaussian beam. Out of several PCGHs designed for Gaussian illumination, two were eventually fabricated: EQ.8 and LN.11.

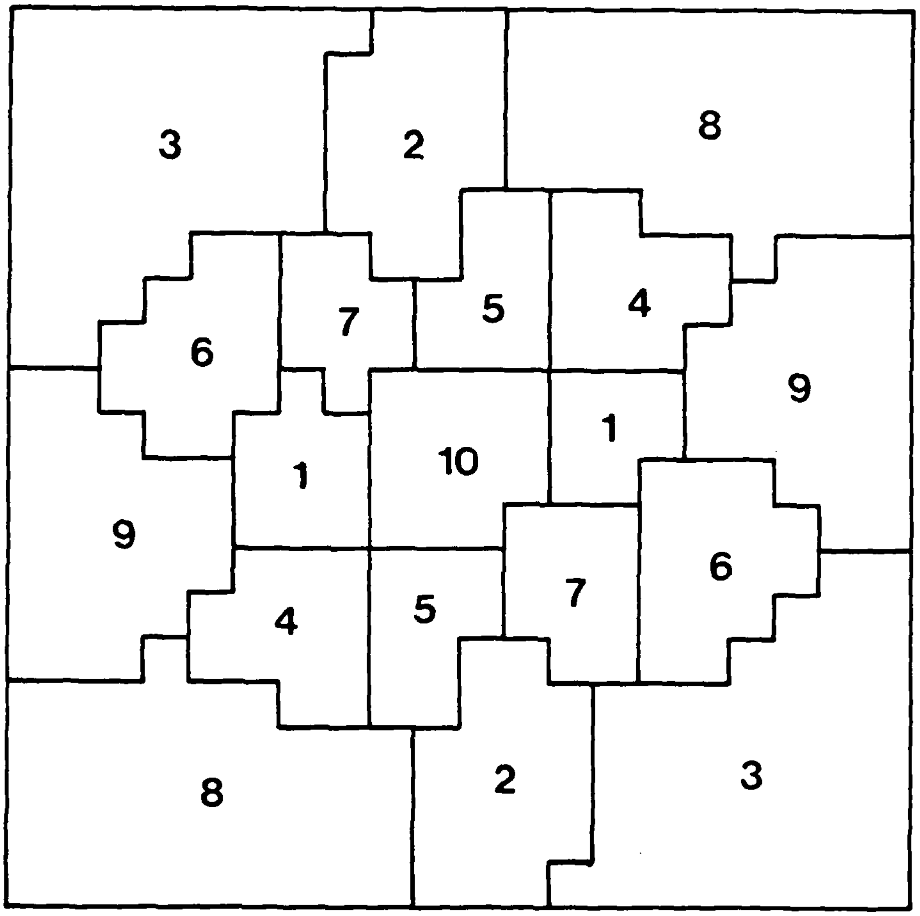

Figure 8. PCGH Design EQ.8. This hologram was designed for Gaussian illumination (diminishing to e^{-4} at the corners) and 10 equal intensity outputs. The central facets are therefore smaller. A high degree of symmetry provides immunity to beam wander.

Like Design No. 2, PCGH EQ.8 was designed for 10 equal outputs. Figure 8 shows the partitioning by subfacets, Figure 9 presents a scan of the diffraction pattern, and Figure 10 is an actual photo of the hologram. The design algorithm predicted uniformity to 12dB, limited by the requirement for partitioning only along subfacet boundaries. In actual fact, we found the outputs to be equal to within 20dB. This result was unexpected and should be considered quite good for an optical computing scheme. Some data fitting no doubt occurred in the process of positioning the PCGH. A discouraging fact was that day to day stability of the setup was not much better than 20dB. The dominant problem was beam wander in the laser, which manifested itself as time-dependent pointing of the Gaussian point source. With this variability, improving the PCGH through trimming proved impossible.

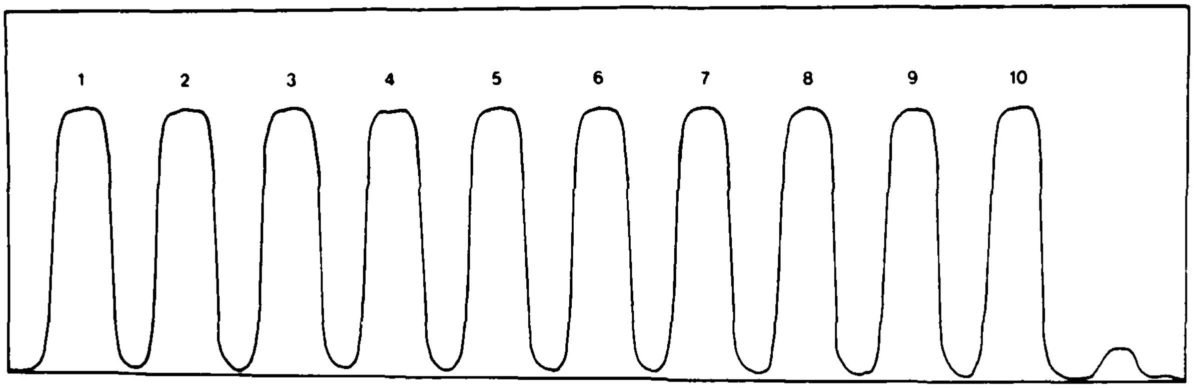

Figure 9. Scan of Diffraction Pattern from PCGH EQ.8. The scan is through the centers of the outputs. The peaks are equal in intensity to better than 20dB with no trimming.

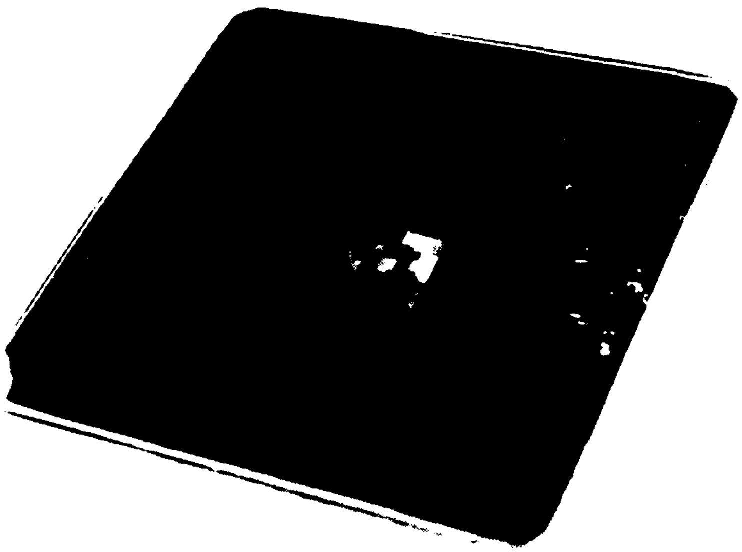

Figure 10. Photo of PCGH EQ.8.

Our objective of pushing the numerical accuracy beyond 20dB demanded that we have a more stable source of illumination. For this reason, the setup was again modified to include a single-mode optical fiber as the point source. The fiber offered a distinct advantage over a pinhole spatial filter; the shape and pointing of the output beam were unrelated to what went on at the input end. Unfortunately, the fiber output distribution is only approximately Gaussian. There were also difficulties in adequately stripping cladding modes and in the increased dependence of intensity on input alignment. Polarization rotation in the fiber may have been an additional noise source that we did not observe.

We evaluated PCGHs EQ.8 and LN.11 using the fiber-optic source. The accuracy of EQ.8 dropped from 20dB to about 7dB due to the different illumination profile. PCGH LN.11 (Figure 11) was designed for Gaussian illumination and nine non-zero outputs spanning a 40-dB numerical range. The measured numerical range was only slightly under 37dB. This was anticipated because, prior to trimming, the two dimmest channels each occupied a full subfacet. The numerical accuracies of the remaining outputs were comparable to those of EQ.8.

With the increased system stability afforded by the optical fiber, we anticipate significant improvement from trimming EQ.8 and LN.11. We have been unable to schedule this task in time for the results to be included in this report, but we do intend to complete the trimming and include the results in a forthcoming paper. We have no plans at present to modify the partitioning algorithms to account for the true illumination profile of the fiber.

ACCOMPLISHMENTS IN 1981

- Developed an approach to optical vector-matrix multiplication using partitioned computer-generated holograms (PCGHs) to achieve large numerical range and high accuracy.
- Developed and implemented PCGH partitioning algorithms to balance requirements for prescribed output intensities, minimal crosstalk, and immunity to beam wander.
- Designed, fabricated, and tested single-input channel PCGHs for
  (a) Uniform illumination, 10 outputs equal to within 3dB
  (b) Gaussian illumination, 10 outputs equal to within 20dB
  (c) Gaussian illumination, 10 outputs spread over a 37-dB numerical range.
- Implemented a method of post-fabrication trimming of PCGHs for amplitude control.

We anticipate additional results which will be presented for publication.

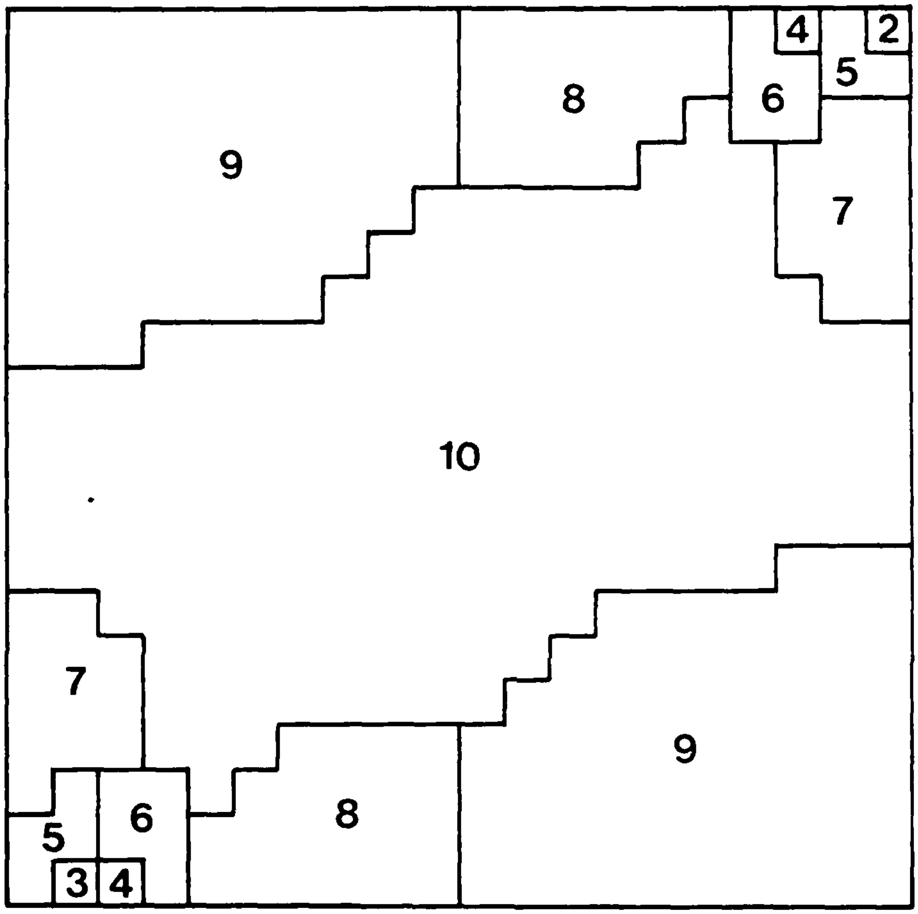

Figure 11. PCGH Design LN.11. This hologram was designed for Gaussian illumination and 9 non-zero outputs spanning a numerical range of 40dB ($y_1 = 0$, $y_m \alpha\ 10^{m/2}$). Channel 10 occupies most of the hologram, while the dimmest channels are located at the corners where intensity is diminished by e^{-4}.

Section IV
Future Plan of the Program

Because of their low weight, small size, and potentially easy replicability, diffractive optical elements are an attractive alternative to conventional optical elements in systems employing monochromatic light. In our previous work, we have shown that e-beam generated HOEs can have very large space-bandwidth products and produce arbitrarily prescribed output waves. The holograms we have generated to date have been binary absorption holograms with efficiencies limited to a theoretical maximum of 10.1 percent. In this next year, we propose to extend our e-beam techniques to produce new types of CGHs offering extremely high diffraction efficiencies. Our specific 1982 objectives are:

- To analyze and develop techniques for fabricating e-beam computer-generated holograms with diffraction efficiencies approaching 100 percent.
- To demonstrate high-efficiency, large numerical aperture, computer-generated holographic optics capable of bringing a collimated He-Ne laser beam to a focus.

The work statement that addresses these objectives is to:

1. Calculate achievable values of diffraction efficiency and numerical aperture for ultra-high frequency, binary-phase HOEs as a function of space-bandwidth product and grating depth.
2. Calculate achievable values of diffraction efficiency and numerical aperture for blazed, crystalline, reflection HOEs as a function of space-bandwidth product and crystal orientation.
3. Develop techniques for ion milling square-wave gratings into glass.
4. Develop techniques for etching blazed gratings into Si and/or GaAs crystals.
5. Fabricate and test high-efficiency, large numerical aperture, computer-generated HOEs for focusing a He-Ne laser beam. These HOEs are to use the techniques developed in Tasks 3 and 4.

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Appendix A
Miscellaneous Information

PUBLICATION IN PREPARATION

"E-beam Generated Holographic Masks for Optical Vector-Matrix Multiplication," S.M. Arnold and S.K. Case, in preparation as a paper to be submitted to **Applied Optics.**

PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

S.M. Arnold, Principal Research Scientist
S.K. Case, Consultant, University of Minnesota, Department of Electrical Engineering.

INTERACTIONS

"E-beam Generated Holographic Masks for Optical Vector-Matrix Multiplication," S.M. Arnold and S.K. Case, paper presented at NASA Conference on Optical Information Processing for Aerospace Applications, Aug. 18-19, 1981, Langley Research Center, Hampton, Virginia.

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